Table 2-1   Key References on Reinforced Concrete Wall Behavior (continued)

Reference	Description	Comp. Types	A	B	C	D	E	F	G	H	I	J	K	L
Paulay, Priestley & Synge (1982)	4 test specimens, 2 rectangular, 2 flanged. Low-rise walls, $M/VL = 0.57$ Approx. 1/2 scale. Two specimens with diagonal bars to prevent sliding shear.	RC1	•			•								
Paulay & Binney (1974) Paulay (1971a, 1971b)	12 coupling-beam test specimens, 3 monotonic loading, 9 cyclic-static loading. $M/VL = 0.51, 0.65$. Approx. 1/2 scale. Varied amount of stirrup reinforcement, and amount and arrangement of longitudinal reinf., 3 specimens with diagonal bars.	RC3	•	•	•	•								
Paulay and Santhakumar (1976)	Two 7-story coupled wall specimens. Cyclic-static loading 1/4 scale. One specimen with diagonally reinforced coupling beams.	RC1 RC3	•			•								
Barney et al (1978) (Portland Cement Association)	8 coupling beam test specimens, Cyclic-static loading. $M/VL = 1.25, 2.5$. Approximately 1/3-scale specimens with conventional longitudinal reinforcement, diagonal bars in hinge zones, and full length diagonal bars. Full length diagonal reinforcement significantly improved performance.	RC3	•	•		•								
Wight (Editor) (1985)	7-story building, two bays by three bays with beam and slab floors, cyclic-static loading full scale. One wall acting parallel to moment frames. Parallel and perpendicular frames increased the capacity of the structure. Test structure repaired with epoxy injection and re-tested	RC1			•									
Alexander, Heidebrcht, and Tso (1973) (McMaster University)	$M/VL = 2.0, 1.33, 0.67$ Cyclic-static loading. 1/2 scale. Axial load varied.	RC1	•			•								
Shiga, Shibata, and Takahashi (1973 ,1975) (Tohoku University)	8 test specimens, 6 cyclic-static loading, 2 monotonic. Approx. 1/4 scale. Barbell section.Load history, web reinforcement, and axial load varied. $M/VL = 0.63$.	RC1			•									
Maier (1991)	10 test specimens, 2 cyclic-static loading, 8 monotonic. 7 flanged sections, 3 rectangular. Approx. 1/3 scale. Reinforcement and axial load varied. $M/VL = 1.12$.	RC1		•	•									

[1] Behavior modes:

A Ductile Flexural Response

B Flexure/Diagonal Tension

C Flexure/Diagonal Compression (Web Crushing)

D Flexure/Sliding Shear

E Flexure/Boundary-Zone Compression

F Flexure/Lap-Splice Slip

G Flexure/Out-of-Plane Wall Buckling

H Preemptive Diagonal Tension

I Preemptive Web Crushing

J Preemptive Sliding Shear

K Preemptive Boundary Zone Compression Failure

L Preemptive Lap-Splice Failure

M Global foundation rocking of wall

N Foundation rocking of individual piers

Table 2-1   Key References on Reinforced Concrete Wall Behavior (continued)

Reference	Description	Comp. Types	A	B	C	D	E	F	G	H	I	J	K	L
Mansur, Balendra, and H'ng (1991)	4 successful test specimens, cyclic-static loading. Approx. 1/4 scale. Flanged section. Web reinforced with welded wire mesh or expanded metal. $M/VL = 0.68$.	RC1		•	•									
Saatcioglu (1991)	3 test specimens, cyclic-static loading Approx. 1/3 scale. Rectangular section. Horizontal and sliding-shear dowel reinforcement varied. $M/VL = 0.50$.	RC1		•	•	•								
Aristizabal-Ochoa, Dario, & Sozen (1976) (University of Illinois)	4 shake-table specimens. Approx. 1/12 scale. 10-story coupled walls, rectangular pier and beam sections. Discusses reduced stiffness of coupling beams resulting from bond slip, and redistribution of demands between wall piers.	RC1 RC3	•											
Lybas & Sozen (1977) (University of Illinois)	6 test specimens, 5 shake-table and 1 cyclic static. Approx. 1/12 scale. 6-story coupled walls, rectangular pier and beam sections.	RC1 RC3	•											
Azizinamini et al. (1994) (Portland Cement Association)	Out-of-plane tests on tilt-up walls. 6 test specimens. Approx. 3/5 scale. Monotonic out-of-plane loading. Report shows typical crack patterns resulting from out-of-plane forces.	RC1												
ACI-SEAOSC Task Force (1982)	Out-of-plane tests on tilt-up walls, 12 reinforced concrete specimens (Also, 18 reinforced masonry specimens). Full scale monotonic out-of-plane loading and constant axial loading h/t ratios of 30 to 60.	RC1												

[1] Behavior modes:

A Ductile Flexural Response

B Flexure/Diagonal Tension

C Flexure/Diagonal Compression (Web Crushing)

D Flexure/Sliding Shear

E Flexure/Boundary-Zone Compression

F Flexure/Lap-Splice Slip

G Flexure/Out-of-Plane Wall Buckling

H Preemptive Diagonal Tension

I Preemptive Web Crushing

J Preemptive Sliding Shear

K Preemptive Boundary Zone Compression Failure

L Preemptive Lap-Splice Failure

M Global foundation rocking of wall

N Foundation rocking of individual piers

2.4   Symbols for Reinforced Concrete

Symbols that are used in this chapter are defined below. Further information on some of the variables used (particularly those noted "per ACI") may be found by looking up the symbol in Appendix D of *ACI 318-95*.

A_{ch} = Cross sectional area of confined core of wall boundary region, measured out-to-out of confining reinforcement and contained within a length c' from the end of the wall, FEMA 306, Section A2.3.7

A_{cv} = Net area of concrete section bounded by web thickness and length of section in the direction of shear force considered, in² (per ACI)

A_g = Gross cross sectional area of wall boundary region, taken over a length c' from the end of the wall, FEMA 306, Section A2.3.7

A_{sh} = Total cross-sectional area of transverse reinforcement (including crossties) within spacing s and perpendicular to dimension h_c. (per ACI)

b = Width of compression face of member, in (per ACI)

b_w = Web width, in (per ACI)

c = Distance from extreme compressive fiber to neutral axis (per ACI)

c' = Length of wall section over which boundary ties are required, per FEMA 306, Section A2.3.7

d_b = Bar diameter (per ACI)

d_{bt} = Bar diameter of tie or loop

f'_c = Specified compressive strength of concrete, psi (per ACI)

f_y = Specified yield strength of nonprestressed reinforcement, psi. (per ACI)

f_{yh} = Specified yield strength of transverse reinforcement, psi (per ACI)

h_c = Cross sectional dimension of confined core of wall boundary region, measured out-to-out of confining reinforcement

h_d = Height over which horizontal reinforcement contributes to V_s per FEMA 306, Section A2.3.6.b

h_w = Height of wall or segment of wall considered (per ACI)

k_{rc} = Coefficient accounting the effect of ductility demand on V_c per FEMA 306, Section A2.3.6.b

l_p = Equivalent plastic hinge length, determined according to FEMA 306, Section A2.3.3.

l_u = Unsupported length considered for wall buckling, determined according to FEMA 306, Section A2.3.9

l_n = Beam clear span (per ACI)

l_w = Length of entire wall or segment of wall considered in direction of shear force (per ACI). (For isolated walls and wall piers equals horizontal length, for spandrels and coupling beams equals vertical dimension i.e., overall depth)

M_{cr} = Cracking moment (per ACI)

M_e = Expected moment strength at section, equal to nominal moment strength considering expected material strengths.

M_n = Nominal moment strength at section (per ACI)

M_u = Factored moment at section (per ACI)

M/V = Ratio of moment to shear at a section. When moment or shear results from gravity loads in addition to seismic forces, can be taken as M_u/V_u

N_u = Factored axial load normal to cross section occurring simultaneously with V_u; to be taken as positive for compression, negative for tension (per ACI)

s = Spacing of transverse reinforcement measured along the longitudinal axis of the structural member (per ACI)

s_l = spacing of vertical reinforcement in wall (per ACI)

V_c = Nominal shear strength provided by concrete (per ACI)

V_n = Nominal shear strength (per ACI)

V_p = Nominal shear strength related to axial load per Section

V_s = Nominal shear strength provided by shear reinforcement (per ACI)

V_u = Factored shear force at section (per ACI)

V_{wc} = Web crushing shear strength per FEMA 306, Section A2.3.6.c

α = Coefficient accounting for wall aspect ratio effect on V_c per FEMA 306, Section A2.3.6.b

β = Coefficient accounting for longitudinal reinforcement effect on V_c per FEMA 306, Section A2.3.6.b

δ = Story drift ratio for a component, corresponding to the global target displacement, used in the computation of V_{wc}, FEMA 306, Section A2.3.6.c

μ = Coefficient of friction (per ACI)

μ_Δ = Displacement ductility demand for a component, used in FEMA 306, Section A2.3.4, as discussed in Section 6.4.2.4 of *FEMA-273*. Equal to the component deformation corresponding to the global target displacement, divided by the effective yield displacement of the component (which is defined in Section 6.4.1.2B of *FEMA-273*).

ρ_g = Ratio of total reinforcement area to cross-sectional area of wall.

ρ_l = Local reinforcement ratio in boundary region of wall according to FEMA 306, Section A2.3.7

ρ_n = Ratio of distributed shear reinforcement on a plane perpendicular to plane of A_{cv} (per ACI). (For typical wall piers and isolated walls indicates amount of horizontal reinforcement.)

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3. Reinforced Masonry

3.1 Commentary and Discussion

Several topics that are relevant to the development of the reinforced masonry component guides are addressed in this chapter.

3.1.1 Typical Hysteretic Behavior

The behavior modes described for reinforced masonry in FEMA 306, Section A3.2 are based on experimental research and field observation of earthquake damaged masonry buildings. Typical damage patterns and hysteretic response representative of different components and behavior modes are presented in Table 3-1

3.1.2 Cracking and Damage Severity

Cracks in a structural wall can provide information about previous displacements and component response. Aspects of cracking that relate to component behavior include:

- The orientation of cracks

- The number (density) of cracks

- The spacing of cracks

- The width of individual cracks

- The relative size of crack widths

In reinforced masonry with a flexural behavior mode, flexural cracks generally form in the mortar bed joints. At the base of a tall cantilever wall, flexural cracks may propagate across the entire length of the wall. Following an earthquake, flexural cracks tend to close due to gravity loads, and they may be particularly hard to locate in mortar joints. They are generally associated with ductile response and the natural engagement of vertical reinforcement; as a result, they do not provide a good measure of damage. When such cracks are visible, they are only used to identify behavior modes, not to assess the severity of damage.

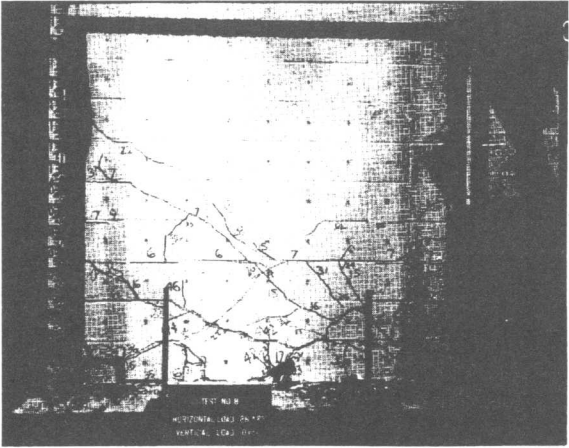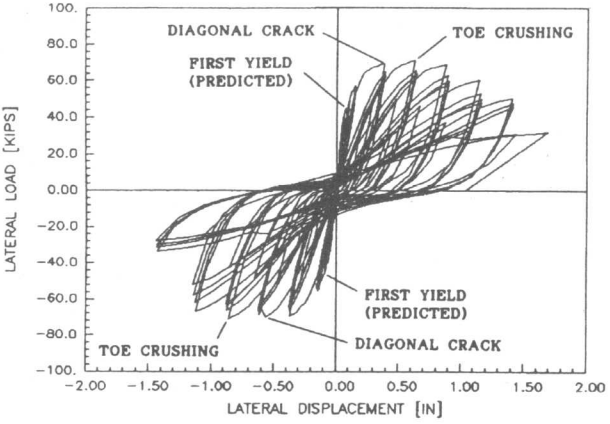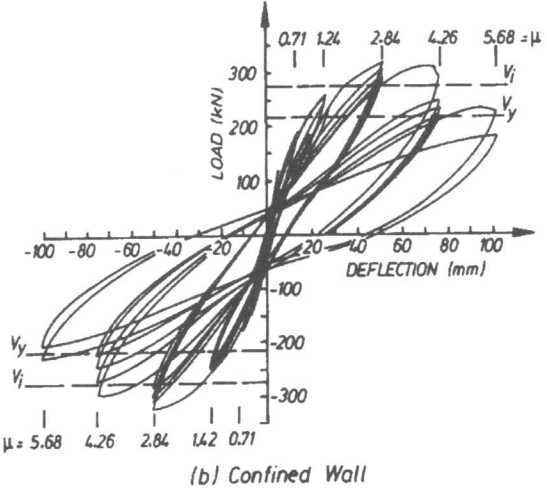Diagonal cracks reflect associated shear stresses, but they may be a natural part of ductile flexural action. In fully-grouted hollow brick or block masonry, diagonal cracks typically propagate through the units with short deviations along the mortar joints. Stair-step diagonal cracks are rare, and would indicate partial grouting and low-strength mortar. In plastic-hinge zones undergoing flexural response, diagonal cracks propagate from the ends of flexural cracks. In shear-dominated panels, diagonal cracks are more independent of flexural cracks.

In a flexurally-controlled wall, diagonal cracks are well-distributed and of uniform, small width. In a wall undergoing the transition from flexural response to shear response, one or two diagonal cracks, typically at the center of the wall, will grow wider than the others, dominating the response and concentrating shear deformations in a small area. A poorly-detailed wall undergoing preemptive shear behavior may have very few cracks until a critical, single diagonal crack opens.

In the investigation of earthquake-damaged concrete and masonry wall structures, cracks are the most visible evidence of damage. Because cracks are a striking and easily observed indication of the effect of earthquakes on walls, there is a strong temptation to overemphasize the relationship between crack width and the associated decrease (if any) in the strength and deformation capacity of a wall. Hanson (1996), has made the case that crack width alone is a poor indicator of damage severity. In recognition of this, the Component Damage Classification Guides in FEMA 306 do not rely on crack width as the only description of damage—numerous indicators of damage severity in reinforced masonry walls are described, among which crack width is only one. Cracking patterns can provide a wealth of information about the performance of a structural wall, but the location, orientation, number, and distribution of the cracks must be considered as important as, if not more important than, the crack width.

With the understanding that crack width must be considered in the context of all of the other parameters that can affect the behavior mode and damage severity of a wall, a rational approach is required to understand the influence of crack width on damage. This section outlines the basis of crack width limits specified in the Component Damage Classification Guides.

Table 3-1   *Damage Patterns and Hysteretic Response for Reinforced Masonry Components*

Component and Behavior Mode	Reference	Crack / Damage Pattern	Hysteretic Response
RM1 Flexure *See Guide RM1A*	Shing et al., 1991 Specimen 12		
RM1 Flexure *See Guide RM1A*	Priestley and Elder 1982		 (b) Confined Wall